Interannual to decadal variability of outflow from the Labrador Sea

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[1] A decade of weak convection in the Labrador Sea associated with decreasing water mass transformation, in combination with advective and eddy fluxes into the convection area, caused significant warming of the deep waters in both the central Labrador Sea and boundary current system along the Labrador shelf break. The connection to the export of Deep Water was studied based on moored current meter stations between 1997 and 2009 at the exit of the Labrador Sea, near the shelf break at 53°N. More than 100 year-long current meter records spanning the full water column have been analyzed with respect to high frequency variability, decaying from the surface to the bottom layer, and for the annual mean flow, showing intra- to interannual variability but no detectable decadal trend in the strength of the deep and near-bottom flow out of the Labrador Sea. **Citation:** Fischer, J., M. Visbeck, R. Zantopp, and N. Nunes (2010), Interannual to decadal variability of outflow from the Labrador Sea, *Geophys. Res. Lett.*, *37*, L24610, doi:10.1029/2010GL045321.

1. Introduction

[2] The Labrador Sea is characterized by a cyclonic boundary current surrounding one of the most active areas of water mass transformation and extending from the sea surface to the bottom. Along the Labrador shelf break the three components of North Atlantic Deep Water (NADW) merge into the Deep Western Boundary Current (DWBC) as part of the cold water limb of the Meridional Overturning Circulation (MOC). Above the DWBC and more confined to the shelf break flows the well known surface current, the equally cyclonic Labrador Current (LC) with its strong baroclinic structure and pronounced seasonal cycle [*Fischer et al.*, 2004]. Below the LC and offshore, in the Labrador Sea Water (LSW) and North East Atlantic Deep Water (NEADW) range, the flow exhibits almost no vertical shear and no detectable seasonality. Near the bottom the flow associated with the Denmark Strait Overflow Water (DSOW) reveals substantial mean currents in a well-defined velocity core [*Fischer et al.*, 2004].

[3] The western boundary transports in the Labrador Sea during 1997–99 were presented by *Fischer et al.* [2004], who established the two-year mean section transports in the different isopycnal ranges of the DWBC at 53°N (near the exit of the Labrador Sea) and reported on intraseasonal variability of currents and transports. The total deep water transport of the DWBC (LSW, NEADW and DSOW) for that time period is of the order of 30 Sv, and uncertainties are in the range of 5 Sv. From LADCP station data *Dengler et al.* [2006] made a rough estimate of longer-term changes of flow in the LSW layer for the first and second half of the time period 1996 to 2005. Their evaluation, despite marginal significance, shows that the DWBC flow during the second half of the period was approx. 10 to 20% higher than during the first period. This agrees well with observations farther north near Hamilton Bank, where *Han et al.* [2010] reported on a transport decrease in the 1990s followed by a later rebound in the early 2000s; there is some temporal overlap with the data presented here.

[4] Furthermore, there was no indication of any successive weakening of the boundary flow as proposed by *Häkkinen and Rhines* [2004] for the early nineties and supported by numerical model studies of these authors, and also by *Böning et al.* [2006].

[5] While the observations during the last decade indicate a weakening of the formation and a decreased vertical extent of deep Labrador Sea Water, the shallower and lighter LSW constituent increased considerably in volume [*Kieke et al.*, 2009]. Recently, as a result of the severe winter season 2007/2008, deep winter convection and associated cooling of the central Labrador Sea resumed [*Våge et al.*, 2009; *Yashayaev and Loder*, 2009]. However, this event appears to be less of a beginning of a new deep convection phase, but instead as an anomaly that should be detectable in both the spreading water mass properties and the boundary current strength.

[6] Here the focus will be on the Deep Water flow variability throughout the full depth range near the exit of the Labrador Sea.

2. Observations and Analysis

[7] For more than a decade, from 1997 to 2009, moored observatories were deployed over varying time intervals and positions at 53°N near the western margin of the Labrador Sea (Figure 1). During mooring servicing cruises, CTD and ADCP/LADCP ship sections yielded transport estimates for the different layers of NADW (Figure 1, right).

3. Moored Current Meter Stations

[8] At the exit of the Labrador Sea, along our main section at 53°N (Figures 1 and 2), moored stations were deployed during summer 1997. For the first two years this array consisted of five moorings covering the flow near the shelf break out to the deep Labrador Sea [*Fischer et al.*, 2004]. During 1999–2003 the array was reduced to three moorings of which the central one was lost during 1999–2001. For 2003–2007 only the central mooring of the initial array (K9, at 2800 m water depth, Figures 1 and 2) was continued.

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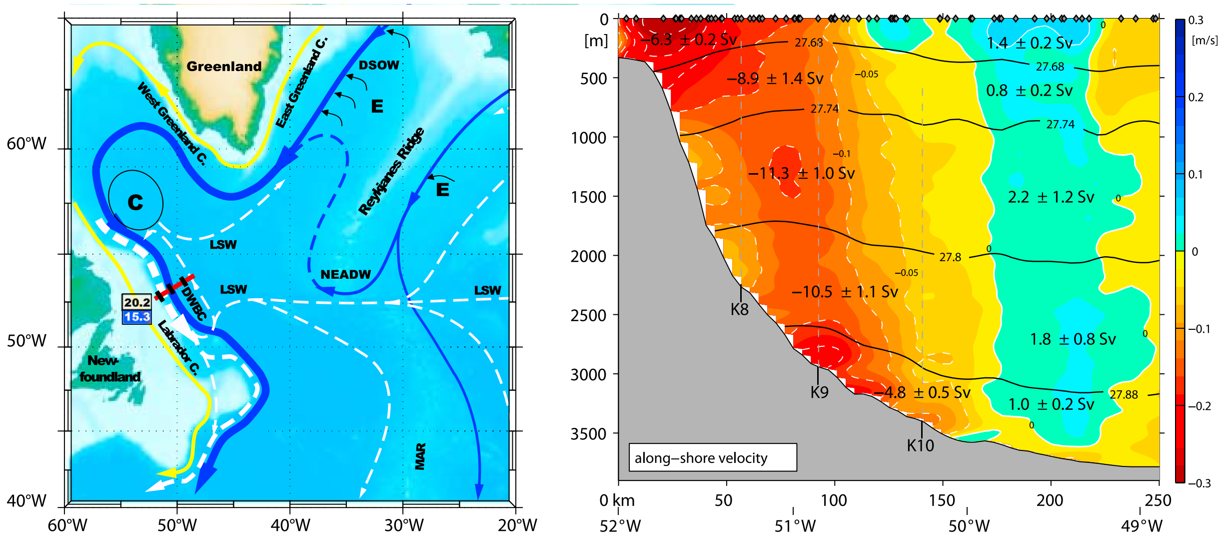

Figure 1. (left) Location at the exit of the Labrador Sea with section and moorings marked along the red line; (right) mean boundary current from a combination of all available LADCP profiles (similar to *Dengler et al.* [2006], but with recent data included). Layer transports with error margins (Sv) as bold numbers; mooring positions K8, K9, and K10 are marked as dashed vertical lines and labeled below the topography; isopycnals (σ_θ) for water mass boundaries (black lines); isotachs (m/s) as white lines, with negative flow toward southeast.

Mooring K8 was at approximately 2200 m water depth and K10 located at 3200 m, the edge of the deep boundary current. There were additional data gaps in the K9 record as shown in Figure 3.

[9] Current measurements were taken at nominal depths of 200 m, 700 m, 1000 m, 1500 m, 2000 m, 2500 m and near the bottom. Additional temperature records are taken on all moorings. All velocity time series were detided by a 40h low-pass filter and subsequently sub-sampled to 12h resolution. In total, there are 109 year-long current records spanning the twelve year time period 1997 to 2009.

4. Shipboard Observations

[10] In the Labrador Sea, two sections running perpendicular to the shelf break were repeatedly occupied during nine cruises: in August 1996, July of 1997, 1998 and 1999, June 2001, September 2003, August 2005, and June 2007. One section ran along the western part of WOCE line AR7W which is also covered annually by BIO scientists [e.g., *Lazier et al.*, 2002], and the other one along the mooring line at 53°N (Figure 1). Station data included conductivity-temperature-depth (CTD) data and direct velocity profiles collected with lowered acoustic Doppler current profilers (LADCP). All LADCP data were post-processed using an inverse technique [*Visbeck*, 2002] that constrained the resulting velocity profiles to on-station shipboard ADCP data when available, and to bottom track velocities [*Dengler et al.*, 2006].

5. Mean Boundary Current Sections From LADCP Data

[11] The time-mean section of currents and subsequent calculations of transports were derived from the above-described shipboard LADCP observations. Figure 1 (right) shows the distribution of alongshore currents (white isotachs, in m s^{-1}), surfaces of potential density as the boundaries between the water masses relevant to this study (black isopycnals, in kg m^{-3}), and volume transports with error bounds for these water masses (bold numbers, in Sv). The locations of current meter moorings used in this paper are indicated in Figure 1. The density layers associated with LSW ranging from σ_θ = 27.68–27.74 kg m^{-3} for the upper (lately ventilated) LSW and σ_θ = 27.74–27.80 kg m^{-3} for the deeper LSW, while NEADW, entering through the Charlie Gibbs Fracture Zone and other passages in the Mid Atlantic Ridge, occupies the density range σ_θ = 27.74–27.80 kg m^{-3}, followed by DSOW as the densest layer [e.g., *Stramma et al.*, 2004].

[12] Two different methods were applied to derive the mean boundary current velocities and transports for water mass layers: the first was a Gaussian interpolation to an equidistant grid using all stations regardless which cruise they came from (Figure 1, right), and second by gridding each individual section and then average these to obtain the mean flow field. The total mean Deep Water transport out to the current reversal was remarkably robust, as the two transport estimates differ only slightly, also compared to the estimates presented by *Dengler et al.* [2006] for a subset of the data. However, the individual section transports allowed for an error estimate of the mean (see Figure 1, right) which is around 1 Sv for each of the layers or 2.2 Sv for the total deep water transport, i.e., less than 10% error of the mean. Second, in comparison with the moored instruments it should be noted that the structure of the boundary current could have changed during the last decade, and in fact the width of the DWBC appears a little broader in the later section occupations, illustrating the magnitude of the short term variability.

[13] At 53°N, the average DWBC transport is 35.5 ± 2.2 Sv and the immediate deep water recirculation sums up to 5.8 ± 1.5 Sv. The 30 Sv total export of NADW

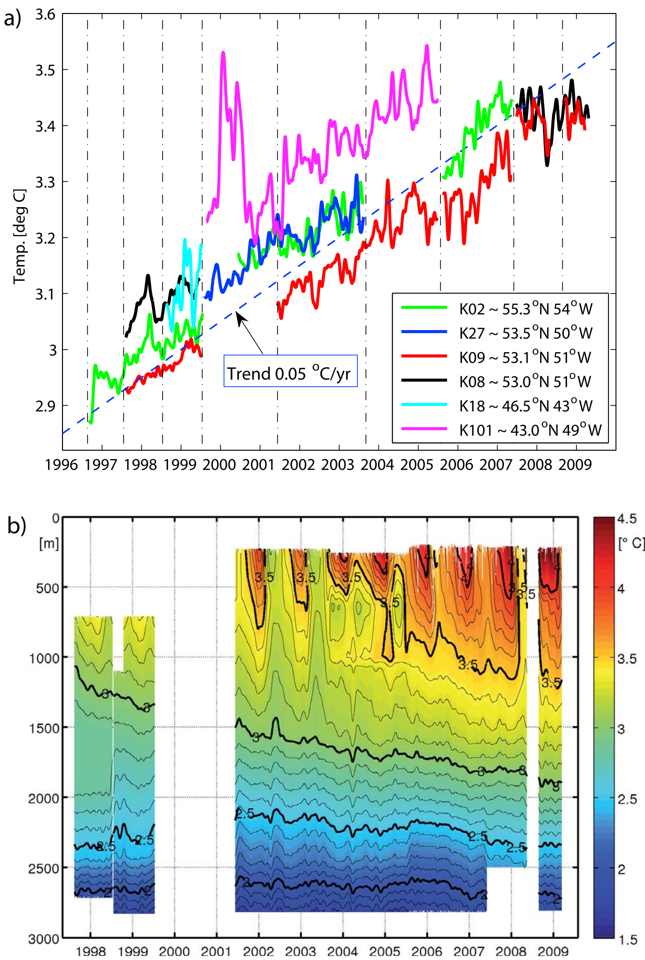

Figure 2. (a) Potential temperature evolution within the DWBC at LSW level, from the Labrador Sea at 55°N to the Grand Banks at 43°N. Records at the exit of the Labrador Sea are from moorings K8 and K9 (black and red lines). (b) Top (200 m) to bottom (DSOW) potential temperature evolution in the center of the boundary current (from mooring K9).

out of the Labrador Sea (DWBC transport minus recirculation) is therefore much larger than needed to supply the deep water limb of the MOC. Most of the total Deep Water transport is in the LSW layer, 20.2 ± 1.7 Sv, and with transports in the anticyclonic recirculation a net LSW export from the Labrador Sea of about 17 Sv results. For the layers below, the budget is around 13 Sv, with 15.3 Sv in the boundary current and 2.8 Sv recirculating.

6. Evolution of the Deep Labrador Current Throughout the Last Decade

[14] The lack of deep convection after the early 1990s resulted in a temperature increase in the center of the Labrador Sea above 2000 m depth. This warming was caused by advection and through lateral mixing by mesoscale eddies [i.e., *Khatiwala and Visbeck*, 2000; *Avsic et al.*, 2006]. The warmer water enters the boundary current and is exported from the Labrador Sea to the Tail of the Grand Banks at 43°N (Figure 2, temperature record at mooring K101).

[15] Along the BC the decadal warming rate is of the order of 0.05°C per year. The longest record (K9, 53°N) and the corresponding time series from farther north (AR7W, K2) show that this trend already began in 1997, and although a temperature drop occurred in conjunction with the more intense convection in Winter 2007/08, the subsequent period still exhibits a continuation of the warming trend.

7. Time Series of Currents

[16] Here we present time series of the alongshore flow (currents rotated to the direction of the topography; Figure 3)

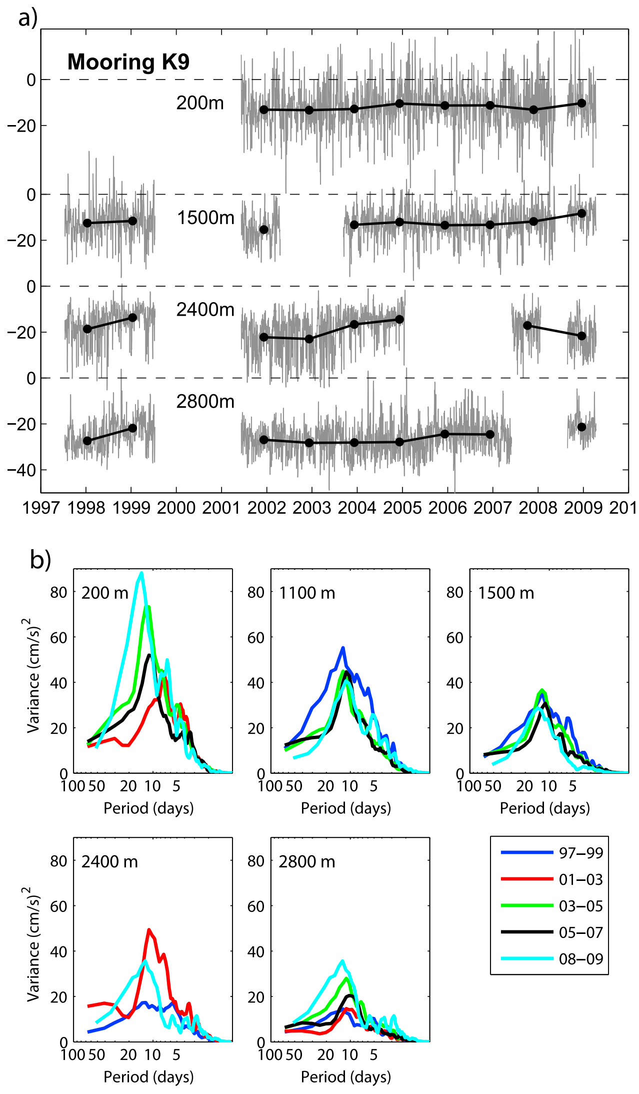

Figure 3. (a) Time series of the alongshore component of the flow at 53°N from mooring K9 and its successors from summer 1997 to summer 2009. Four depth levels have been selected: Upper Layer (200 m), Labrador Sea Water (1500 m), North East Atlantic Deep Water (2400 m) and at the level of Denmark Strait Overflow Water (~2800 m); dotted lines for zero-reference of each time series. Thin grey lines for detided records at 12 h resolution, and black dots for annual mean flow. (b) Spectra of the alongshore currents from mooring K9 in the center of the boundary current. Spectra are calculated for two year periods and five depth layers.

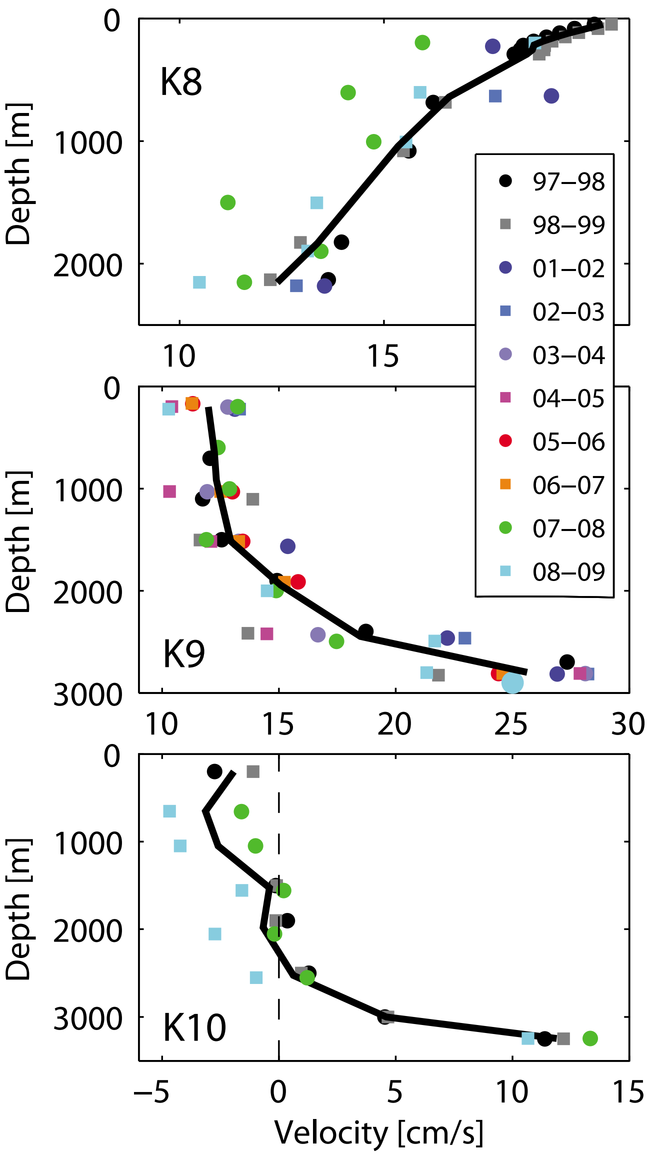

Figure 4. Annual mean flow near 53°N from mooring K8, K9, K10 (see Figure 1 for location). Currents are rotated to mean direction along the topography at the mooring site. Heavy black line for long term average ('decadal' average for K9) of all records.

in the center of the deep boundary current. At this location (see mooring K9 in Figure 1) the flow is weakly baroclinic in the top layer, as it is located at the offshore rim of the shallow Labrador Current. At mid depth the shear is rather weak, but below 2000 m the nature of the flow is baroclinic again, with maximum strength of the flow in the DSOW layer. All records exhibit relatively stable flow toward the exit of the Labrador Sea, and current reversal (i.e., into the Labrador Sea) occurs only sporadically at high frequencies. At low frequencies (annual and longer time scales) the flow is always directed toward Flemish Cap.

8. Intraseasonal Variability

[17] The velocity time series reveals intense short term fluctuations of the boundary current. Here, we are interested in the magnitude of these fluctuations, dominant frequency, their vertical structure, and any long term variations of the eddy variability. Therefore, spectra of the alongshore variability are calculated for two year long segments with averaging over subsets of 128-days duration (Figure 3b). Usually there is a spectral peak at periods around 10 to 20 days and rapid decay of energy toward longer and shorter periods. The highest energy levels are observed near the surface at 200 m depth. The energy (variance) decays toward the bottom where the lowest variability is observed, although the mean flow is strongest. This is for example different from the observations farther downstream the DWBC at the Tail of the Grand Banks – there, the variance increases toward the bottom where the mean flow is rather weak [*Schott et al.*, 2006, Figure 3].

9. Annual Mean Flow and Bottom Intensification

[18] For each year of the deployment, and for each of the three moorings (K8, K9 and K10) annual means of the alongshore flow are plotted versus depth in the color code of the respective year (Figure 4). Nearest to the shelf break, at K8, the flow is decaying from the surface maximum, associated with the edge of the Labrador Current, toward the bottom. Annual means are always directed out of the Labrador Sea. This station was only occupied at the beginning of the deployment period, and most recently, and the initial phase (1997–99) shows almost the same flow as in 2008–2009, but the year 2007–2008 reveals somewhat weaker flow (by about 0.025 m/s or 20% of the mean) throughout most of the water column. The water depth at this location is about 2000m and thus too shallow for any DSOW contribution.

[19] The profiles at mooring K9 (center of the DWBC) show two vertical regimes, one with very little shear from near surface down to 1500 m with a mean of about 0.125 m/s and a more baroclinic layer beneath. The 700 m level was not regularly equipped explaining the small scatter at that level. Shears increase throughout the NEADW layer toward 2500 m depth and strong shears are observed in the near bottom flow associated with the core of the DSOW. Maximum flow in this layer is about 100 m above the bottom (a rough estimate given the distribution of the instruments and individual LADCP profiles at that location). At this level the flow is remarkably high (annual means between 0.22 and 0.27 m/s, and no current reversal) and the scatter around the 'decadal' mean is in the 10% range. Inspection of mooring K10 (the most offshore one) shows that the upper and LSW levels were located in the recirculation; although rather weak, and accordingly the annual mean flow is in opposite direction of the BC, i.e., into the Labrador Sea. This recirculation appears somewhat stronger during the last record and the zero crossing of the flow occurred at greater depth. This indicates that the DWBC was somewhat narrower during 2008/09. However, at DSOW levels, currents are directed out of the Labrador Sea at relatively stable amplitudes around 0.12 m/s indicating that the DSOW current core extends a little further into the basin than K10.

[20] We use the data from K9 to estimate long-term statistics of the flow. With respect to the total (decadal) mean profile we calculated the rms difference of individual years relative to the long term mean in two different ways: first we

calculate the rms difference between individual annual profiles and the decadal profile (resulting in rms values around 0.01 m/s), and second we estimated the rms difference in depth layers, also showing values around 0.01 m/s for the upper 2000 m and around 0.03 m/s in the near bottom layer.

10. Summary and Conclusions

[21] More than 10 years of boundary current measurements from 109 yearlong current meter records near the exit of the Labrador Sea were analyzed with respect to interannual to multiyear variability of the deep flow along the Labrador shelf break. The period is characterized by relatively weak convection in the central Labrador Sea leading to significant warming by advection and eddy fluxes of heat within the LSW layer. This warming is also evident in the boundary current, and only a single winter (2007/2008) interrupted the decadal warming trend.

[22] The flow in all depth layers shows high frequency variability at time scales of weeks, which varies interannually. The deep flow at DSOW levels reveals less short-term variability and no systematic changes (trends) in energy level over the last decade, although the mean flow was most intense at that level. Similarly, the annual mean flow varies at all depth levels by the order of 10% relative to the 'decadal' mean, and again there are no detectable systematic trends in the boundary current intensity. With respect to the anomalous winter of 2007/08, clearly detectable in water mass characteristics, our measurements do not reveal any clear anomaly in the flow field; the only indication of a possible response being a stronger recirculation in 2008/09 and an associated narrower DWBC during that period. Given the error estimates of the LADCP section, and the rms deviations of annual mean currents relative to the decadal mean (of mooring K9) we would have been able to detect long term trends of the order of 10% of the mean flow/transports (these are 1cm/s in annual mean velocity or about 3 Sv as total DWBC transport), but these did not occur during the period investigated here. However, given the robustness of the DWBC, the exit of the Labrador Sea seems like an ideal place for sustained long term observations near the northern origin of the DWBC in the subpolar North Atlantic.

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References

Avsic, T., J. Karstensen, U. Send, and J. Fischer (2006), Interannual variability of newly formed Labrador Sea Water from 1994 to 2005, *Geophys. Res. Lett.*, *33*, L21S02, doi:10.1029/2006GL026913.

Böning, C. W., M. Scheinert, J. Dengg, A. Biastoch, and A. Funk (2006), Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning, *Geophys. Res. Lett.*, *33*, L21S01, doi:10.1029/2006GL026906.

Dengler, M., J. Fischer, F. A. Schott, and R. Zantopp (2006), Deep Labrador Current and its variability in 1996–2005, *Geophys. Res. Lett.*, *33*, L21S06, doi:10.1029/2006GL026702.

Fischer, J., F. Schott, and M. Dengler (2004), Boundary circulation at the exit of the Labrador Sea, *J. Phys. Oceanogr.*, *34*, 1548–1570, doi:10.1175/1520-0485(2004)034<1548:BCATEO>2.0.CO;2.

Häkkinen, S., and P. B. Rhines (2004), Decline of subpolar North Atlantic circulation during the 1990s, *Science*, *304*, 555–559, doi:10.1126/science.1094917.

Han, G., K. Ohashi, N. Chen, P. G. Myers, N. Nunes, and J. Fischer (2010), Decline and partial rebound of the Labrador Current 1993–2004: Monitoring ocean currents from altimetric and CTD data, *J. Geophys. Res.*, *115*, C12012, doi:10.1029/2009JC006091.

Khatiwala, S., and M. Visbeck (2000), An estimate of the eddy-induced circulation in the Labrador Sea, *Geophys. Res. Lett.*, *27*, 2277–2280, doi:10.1029/1999GL011073.

Kieke, D., B. Klein, L. Stramma, M. Rhein, and K. P. Koltermann (2009), Variability and propagation of Labrador Sea Water in the southern subpolar North Atlantic, *Deep Sea Res., Part I*, *56*, 1656–1674, doi:10.1016/j.dsr.2009.05.010.

Lazier, J., R. Hendry, A. Clarke, I. Yashayev, and P. Rhines (2002), Convection and restratification in the Labrador Sea, 1990–2000, *Deep Sea Res., Part I*, *49*, 1819–1835, doi:10.1016/S0967-0637(02)00064-X.

Schott, F. A., J. Fischer, M. Dengler, and R. Zantopp (2006), Variability of the Deep Western Boundary Current east of the Grand Banks, *Geophys. Res. Lett.*, *33*, L21S07, doi:10.1029/2006GL026563.

Stramma, L., D. Kieke, M. Rhein, F. Schott, I. Yashayaev, and K. P. Koltermann (2004), Deep Water changes at the western boundary of the subpolar North Atlantic during 1996 to 2001, *Deep Sea Res., Part I*, *51*, 1033–1056, doi:10.1016/j.dsr.2004.04.001.

Våge, K., R. S. Pickart, V. Thierry, G. Reverdin, C. M. Lee, B. Petrie, T. A. Agnew, A. Wong, and M. H. Ribergaard (2009), Deep convection returns to the subpolar North Atlantic, *Nat. Geosci.*, *2*(1), 67–72, doi:10.1038/ngeo382.

Visbeck, M. (2002), Deep velocity profiling using lowered acoustic Doppler current profilers: Bottom track and inverse solutions, *J. Atmos. Oceanic Technol.*, *19*, 794–807, doi:10.1175/1520-0426(2002)019<0794:DVPULA>2.0.CO;2.

Yashayaev, I., and J. W. Loder (2009), Enhanced production of Labrador Sea Water in 2008, *Geophys. Res. Lett.*, *36*, L01606, doi:10.1029/2008GL036162.

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